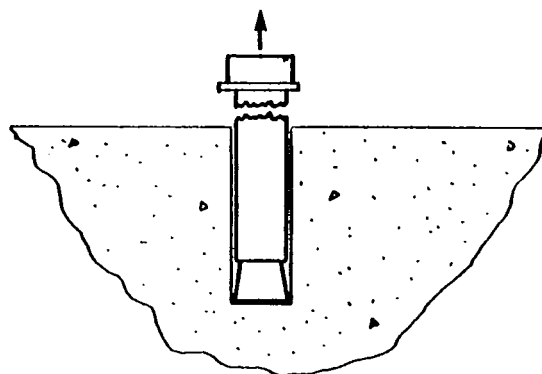
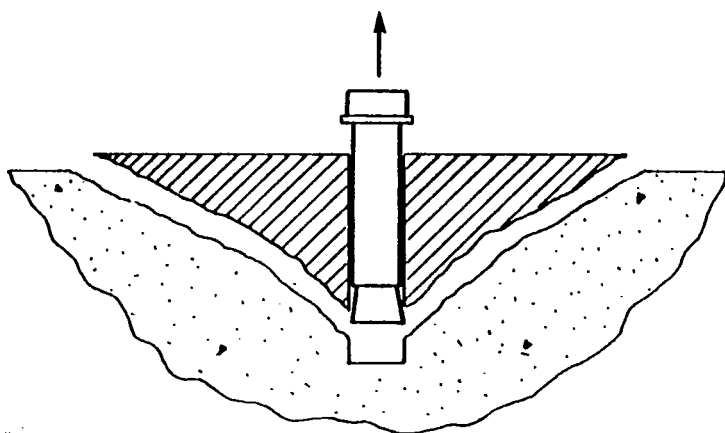


Anchors in Concrete— Design and Behavior



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Editors

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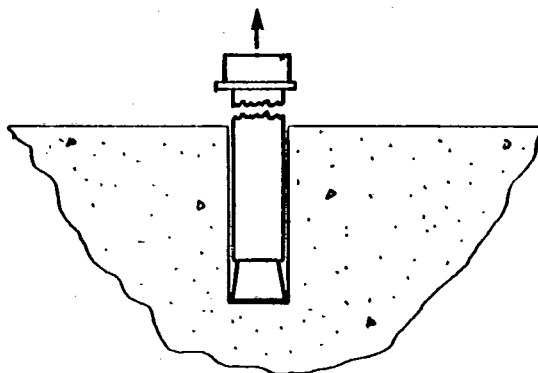
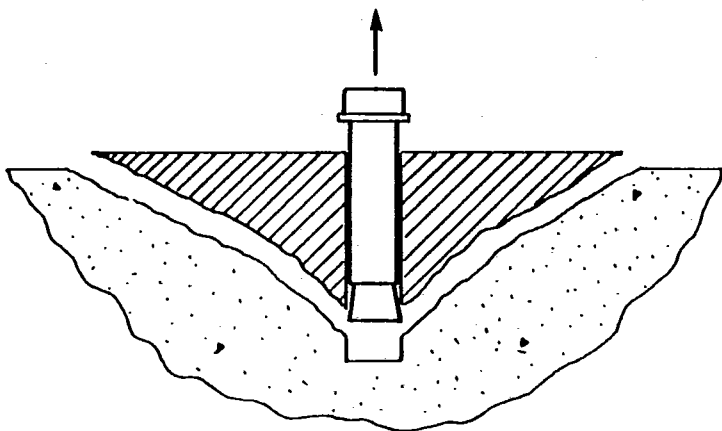
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Anchors in Concrete— Design and Behavior



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PREFACE

The eleven papers in this volume are primarily from two symposiums sponsored by ACI Committee 355, Anchorage to Concrete. The symposiums were held during the American Concrete Institute conventions in San Diego (1989) and Toronto (1990). This volume is the second issue of symposium proceedings on the topic of anchorage to concrete that ACI Committee 355 has published. The first volume, ACI SP-103 "Anchorage to Concrete," was published in 1987 with Gerard B. Hasselwander as editor.

The editors wish to acknowledge the work of all the authors and reviewers. Each paper was reviewed in accordance with ACI publication policy. Unfortunately, several papers presented at the two symposiums were not accepted due to publication elsewhere or due to the proprietary nature of the product.

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Harry B. Lancelot, III
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SP 130-1

Design Guidelines for Anchorage to Concrete

by H. Wiewel

Synopsis: Design information for concrete anchors is summarized in this paper. Based on recent research, the tension and shear capacities published in the past for concrete anchors are generally unconservative, especially data for proprietary concrete anchors. This paper recommends new design parameters for seven categories of concrete anchors. The parameters, presented in tabular form, are related to tension zone cracking, seismic loading, as well as spacing and edge distance.

Keywords: Anchors (fasteners); shear strength; tensile strength; tension; working stress method

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INTRODUCTION

The designer who specifies concrete anchors today is faced with choosing from a larger variety of concrete anchors than ever before. At the same time, new and stricter test standards result in data that varies substantially from older test results. Not surprisingly, the designer is often frustrated by the variation in published load capacities of similar concrete anchors installed in the same type and strength of concrete.

It is common to see a variation in published anchor capacities for similar anchors produced by different manufacturers because of the variation in concrete and installation practices followed during testing. Data published for wedge anchors by ICBO Evaluation Services, Inc. (Ref. 1) show that 3/4" diameter wedge anchors range in allowable tension capacity from 2420 to 3500 lbs and allowable shear capacity from 1750 to 5440 lbs. This reflects the variations in manufacturer published data. However, when several of the wedge anchors listed in the ICBO ES evaluation reports were tested under identical conditions (Ref. 2), the range in ultimate tension and shear capacities was much smaller than the values published by ICBO ES.

DESIGN METHODS

Both working stress and strength design methods are currently used in the United States to design structural components. The working stress method utilizes proprietary data provided by manufacturers of concrete anchors or data published by organizations such as ICBO Evaluation Service, Inc. (Ref. 1). Working stress methods account for anchor placement and provide for reduction factors accounting for spacing of anchors in groups and edge distances. The strength design method is an analytical approach that utilizes prediction equations as done in Section 2624 of the 1988 Uniform Building Code (Ref. 3), the PCI Design Handbook (Ref. 4), and Appendix B of ACI 349-85, Code Requirements for Nuclear Safety Related Concrete Structures (Ref. 5).

WORKING STRESS METHOD

Testing Requirements

Concrete anchors are typically tested in the United States under ideal conditions. Test samples are installed in concrete slabs simulating the compression zone of a structural member. Average ultimate test values are frequently based on as few as three tests.

The 1976 and 1981 ASTM test standard for concrete

anchors, as well as the ICBO ES, Inc. "Standard for Testing Expansion Anchors in Concrete" (Ref. 6), did not address developing the influence of edge distance.

The minimum edge distance to obtain full shear capacity varies for the different types and sizes of anchors, as well as for different embedment depths. The minimum edge distances recommended in the past by most manufacturers were based on limited test data and are generally unconservative. In 1984 and again in 1988, the ASTM test standard for concrete anchors, Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements (E 488) (Ref. 7), was revised requiring that all anchors be tested at specified edge distances determined by the embedment depth of the anchor. Testing to obtain data for edge distances and spacing of anchors is also addressed by ASTM E 488-84.

Tests performed in accordance with ASTM E 488-84 have indicated that the shear capacity of anchors installed at an edge distance of six anchor diameters is as much as 40% lower than the shear capacity when the edge distance is 10 anchor diameters (Ref. 2).

Design Data

Most of the published data on anchor capacity is provided by the manufacturers of proprietary concrete anchors. The published data is usually based on tests performed or witnessed by an independent testing agency. Typically the manufacturer's literature suggests that the designer use a design value of 25% of the anchor's ultimate shear and tensile capacity.

The best sources for design data on proprietary concrete anchors are the evaluation or research reports published by organizations like ICBO Evaluation Services, Inc. (ICBO ES) and Southern Building Code Congress International (SBCCI). These reports are based on test data provided by the manufacturers.

Table 26-F of the 1988 Uniform Building Code lists values (working stress method) for cast-in-place bolts and requires a minimum edge distance of 6 anchor diameters (6D) to avoid considering a reduction due to edge effects. The edge distance may be reduced by as much as 50 percent (3D) provided that the listed design values are also reduced in equal proportion. These edge distance requirements are also used by ICBO Evaluation Services, Inc. for most of the evaluation reports on proprietary concrete anchors.

Spacing and Edge Distances

Tables 1 and 2 list recommended edge and spacing distances for different categories of concrete anchors in stone aggregate concrete installed at three different ranges of anchor embedment (Ref. 8 & 9). Table 1 tabulates edge and spacing requirements for anchors subjected to shear load and Table 2 tabulates edge and spacing requirements for anchors subjected to tensile load. The tabulated edge distances should be increased when softer aggregates (i.e. lightweight) are used in the concrete mix.

The listed edge distances in Tables 1 and 2 for all anchors, except deformation-controlled expansion anchors (Type E), may be reduced up to 50 percent, provided that the design values are also reduced using the reduction factors listed in Table 3.

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Edge distances for deformation-controlled expansion anchors (Type E) should not be less than those listed in Tables 1 and 2 because these anchors subject the concrete to very high expansion forces during installation which may cause the concrete to crack when installed at reduced edge distances. Expansion anchors, such as wedge and sleeve expansion anchors (Types C and D) or undercut anchors (Type B), are not recommended for installation at edge distances less than 50% of what is listed in Tables 1 and 2. When an application requires edge distances less than 50% of the recommended edge distances, cast-in-place (Type A) or chemical anchors (Type F) should be used and site-specific tests should be performed to verify their design capacity. Reinforcement should be provided in all areas of potential failure planes when specifying Type A anchors at edge distances less than 50% of the recommended edge distances.

Combined Loading

Three design equations are currently in use when an anchor or group of anchors is simultaneously subjected to both shear and tension loading. They are the straight-line, elliptical curve, and tri-linear interaction equations. The straight-line method, represented by equation 1, is the most conservative approach.

Straight Line Method

$$(P/P_{all}) + (V/V_{all}) \leq 1.0 \quad (1)$$

where P = applied tensile load
 V = applied shear load
 P_{all} = tensile design strength of anchorage
 V_{all} = shear design strength of anchorage

Elliptical Curve Method

$$(P/P_{all})^x + (V/V_{all})^y \leq 1.0 \quad (2)$$

where $x = y = 5/3$

Tri-linear Equation

$$(P/P_{all}) \leq 1.0$$

$$(V/V_{all}) \leq 1.0 \quad (3)$$

$$(P/P_{all}) + (V/V_{all}) \leq 1.2$$

STRENGTH DESIGN METHOD

This section is a summary of the strength design approach currently (1989) followed in the United States. The equations listed in this section are generally based on the strength design approach of ACI 349 Appendix B.

The ultimate shear and tensile capacity of a concrete anchor is dependent on one or more of the following factors: anchor type, placement with respect to an edge or corner of the concrete structural member, concrete compressive and/or tensile strength, aggregate type, anchor material, location and size (if any) of steel reinforcement in the structural member and anchor embedment depth.

Also affecting the tensile capacity is whether the anchor is located in the tension zone or compression zone of the structural member. The ultimate tensile capacity of anchors installed in the tension zone of a structural member can be affected by cracks in the area of the anchorage. This must be taken into account when determining the load capacity of a concrete anchor (see section on cracked concrete).

Shear Capacity

The displacement characteristics of anchors loaded in shear depend on the type of anchor, the amount of preload applied, and the amount of load relaxation that has taken place. The preload creates a friction force between the baseplate (or attachment) and the concrete surface. The friction forces must be overcome before the baseplate moves and comes in bearing contact with the anchor. The concrete surrounding the anchor near the surface crushes and creates a small surface spall, allowing the anchor to displace. As the anchor continues to displace, it fails either the concrete or steel, depending on edge distance, type of anchor, steel strength, concrete strength, and/or anchor embedment depth.

Shear failures of the bolt material are common for stud anchors manufactured from softer steels or anchors surrounded by steel shells. The concrete usually crushes a small amount ahead of the anchor in the direction of the shear load. Generally a smooth shear failure plane occurs in the stud as the steel reaches its ultimate shear capacity (see Fig. 1).

The shear design strength of an anchor based on a steel failure (V_s), can be determined from equation 4.

$$V_s = 0.55 (f_y \times A_s) \quad (4)$$

The shear strength of an anchor, when based on a steel failure (V_{su}), can be estimated from equation 5.

$$V_{su} = N (f_{ut} \times A_s) \quad (5)$$

where $0.6 \leq N \leq 0.7$

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Bending rupture failures occur when the concrete surrounding the anchor crushes, allowing the anchor to bend and the steel to rupture in shear (see Fig. 2). This type of failure is common for anchors manufactured from hard brittle steels. Bending/pullout failures occur when the concrete surrounding the anchor crushes, allowing the anchor to bend and pull out of the concrete. This type of failure is common for anchors manufactured from soft ductile steels.

Concrete breakout failure (see Fig. 3) usually occurs when anchors are installed at edge distances less than 10 anchor diameters and the anchor is loaded in the direction at the free edge. The shear design strength of an anchor based on a concrete (breakout) failure (V_d) can be determined from equation 6.

$$V_d = 4\phi \sqrt{f'_c} \times (A_p/2) \quad (6)$$

The ultimate shear strength of an anchor based on a concrete (breakout) failure (V_c) can be estimated from equation 7.

$$V_c = 4 \sqrt{f'_c} \times (A_p/2) \quad (7)$$

Anchors installed in thin, unreinforced slabs and beams may result in a split structural member where the concrete slab or beam fails in bending (see Fig. 4). Anchors installed in thick slabs at edge distances greater than those listed in Table 1 usually result in anchor failures, including shear, bending/rupture, and bending/pullout failures.

Tensile Capacity

There are four basic failure modes for anchors subjected to tensile loading. They are steel fracture, brittle (cone) failure, concrete splitting failure, and slip (pullout) failure. In addition, chemical and grouted anchors can also experience bond failures.

The type of failure mode affects the tensile capacity of the anchor fracture.

Steel Fracture: Steel fracture is a type of failure common for undercut, chemical, cast-in-place, and heavy-duty expansion anchors. In a steel failure, the concrete does not fail and a steel failure occurs when the steel reaches its ultimate tensile capacity (see Fig. 5). Anchors are generally installed at embedments of 9 anchor diameters (9D) or more.

The tensile design capacity of an anchor based on a steel failure can be determined from equation 8.

$$P_s = 0.9 f_y \times A_s \quad (8)$$

The ultimate tensile capacity of an anchor based on a steel failure can be estimated from equation 9.

$$P_t = f_{ut} \times A_s \quad (9)$$

Concrete Cone Failure - Brittle Failure: The concrete fails in tension creating a cone (see Fig. 6). This type of failure usually occurs when anchors are manufactured from high strength steels or for anchors installed at shallow embedments. Cone failures are also common for anchor groups or individual anchors installed near an edge. The cone generally starts at the outer edges of the anchor head or expansion mechanism and travels to the concrete surface at an angle between 30 to 45 degrees with respect to the horizontal surface. The concrete cone has a shape which is steeper near the embedded portion of the anchor and flattens out near the surface of the structural member. Anchor embedment also has an effect on the shape of the cone which tends to have a steeper inclination angle as the embedment is increased.

A cone with an inclination angle of 45 degrees is generally accepted in the United States for estimating the pullout strength of the anchor. The tensile design strength of an anchor based on a concrete (cone) failure can be determined from equation 10.

$$P_d = 4\phi \sqrt{f'_c} \times A_p \quad (10)$$

The ultimate tensile capacity of an anchor based on a concrete (cone) failure can be estimated from equation 11.

$$P_c = 4 \sqrt{f'_c} \times A_p \quad (11)$$

Concrete Failure - Split Structural Member: In this failure mode the concrete slab or beam fails in bending. This type of failure is common for anchors installed in thin, unreinforced slabs and beams, or anchors installed near an edge or corner (see Fig. 7). The anchor capacity is greater than the load causing the structural member to fail in flexure.

Slip Failure: The concrete in contact with the headed portion of a cast-in-place anchor or with the expansion mechanism of a post-drilled anchor fails in compression allowing the anchor to pull out of the hole.

Bond Failure: Bond failures are common for chemical and grouted anchors. This type of failure is usually accompanied by a shallow concrete cone with a depth up to one-half of the total stud embedment (see Fig. 8).

Edge Distance and Spacing Requirements

Appendix B of ACI 349-80, Code Requirements for Nuclear Safety Related Structures requires that the minimum edge distance (m_y) for development of the full shear capacity is determined in accordance with equation 12. The commentary also requires that the minimum edge distance (m_k) to prevent bursting failure (tension loading) is determined in accordance with equation 13. Both equations take into account anchor steel strength, concrete compressive strength, and anchor diameter in determining a minimum edge distance for full shear capacity.

$$m_y = D \sqrt{\frac{f_{ut}}{7.5\sqrt{f'_c}}} \quad (12)$$

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$$m_t = D \sqrt{\frac{f_{ut}}{56\sqrt{f'_c}}} \quad (13)$$

The 1988 Uniform Building Code (UBC) and the Prestressed Concrete Institute (PCI) Design Manual both require an edge distance equivalent to the anchor embedment ($m_t = E$) and spacing equal to two times anchor embedment ($S = 2E$) for full tensile capacity for concrete anchors installed in stone aggregate (granite) concrete when using the strength design method. The Uniform Building Code also requires an edge distance equivalent to ten anchor diameters ($m_t = 10 D$) and spacing equal to two times anchor embedment ($S = 2E$) for full shear capacity for concrete anchors installed in stone aggregate concrete when using the strength design method.

CRACKED CONCRETE

Locating an anchor relative to a crack or potential cracking should be accounted for in design. There is no U.S. requirement currently however, this is a design consideration in Europe. Anchors to be located in the tension zone of a structural member should be able to function in cracked concrete. Similarly, anchors used in structures which may be subjected to seismic loading should also function in concrete which may experience cracking up to 3 mm in width. Recent research has provided information on cracking in a concrete structural member and how it affects the ultimate tensile and shear capacity of the anchor (Ref. 10). The reduction in capacity of an anchorage (single or group) due to the concrete cracking is dependent on such variables as anchor type and the size of the crack. Table 4 lists ranges in reduction (in percent) various anchor types can expect in tensile capacity. The table lists two crack widths, the first of which (0.4 mm) can be expected to occur in the tension zone of a structural member. The second crack width (0.8 mm) can occur during a seismic event.

In general, anchor types whose ultimate tensile capacity in cracked concrete falls below 50% of the ultimate capacity in uncracked concrete are not recommended (NR) when the structural member may experience cracking. Applications requiring anchorage in the tensile zone should be limited to Types A, B, and C anchors and their design capacity should be reduced in accordance with the percentages listed. Other anchor types can be specified for use in the tension zone if a manufacturer can establish through tests that their product has a known capacity in cracked concrete. Concrete anchors used in structures which are located in seismic Zones 3 and 4 should also be evaluated for performance in cracked concrete (Fig. 9). The information listed in Table 4 is based on limited test data and only applies to tensile loads. Although very little data is available on shear capacity of anchors in cracked concrete, it is expected that cracks have a much smaller influence on the ultimate shear capacity than they have on the ultimate tensile capacity of concrete anchors.

RECOMMENDATIONS

The author recommends that concrete anchors be rated according to type, size, and concrete strength. Anchors should also be rated for use in cracked concrete (tension zone, seismic) or uncracked concrete (compression zone). An appropriate safety factor, based on the test data and the coefficient of variation of the tests should be applied to determine allowable working loads. This approach assures that similar anchors have the same allowable working loads. Approval and listing agencies should also establish a quality assurance program to ensure that the listed anchors are not changed after the anchors are tested.

The strength design provisions of the 1988 Uniform Building Code and Appendix B of ACI 349-85, Code Requirements for Nuclear Safety Related Concrete Structures should be expanded to provide provisions for post-installed concrete anchors. Design guidelines for concrete failure due to shallow embedment of concrete anchors should also be included in the strength design provisions of the codes.

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NOTATION

A_b	=	area of anchor bolt head, in ² .
A_p	=	projected area of stress cone using an inclination angle of 45 deg., in ² .
A_a	=	tensile stress area of threaded anchor, in ² .
D	=	anchor diameter, in.
E	=	anchor embedment, in.
f'_c	=	concrete compressive strength, psi.
f_{ut}	=	minimum specified tensile strength of anchor steel, psi.
f_y	=	minimum specified yield strength of anchor steel, psi.
F_t	=	tension load reduction factor, dimensionless.
F_v	=	shear load reduction factor, dimensionless.
F	=	width across flats of bolt head, in.
L_d	=	anchor development length, in.
P_d	=	tensile design strength of concrete, (concrete failure), lbs.
P_c	=	ultimate tensile strength of anchor (concrete failure), lbs.
P_s	=	tensile design strength of anchor, (steel failure), lbs.
P_t	=	ultimate tensile strength of anchor (steel failure), lbs.
N	=	shear strength factor
m	=	edge distance or side cover distance measured from the center line of the anchor to edge, in.
m_t	=	minimum required anchor edge distance to attain full shear capacity, in.
m_v	=	minimum required anchor edge distance to attain full shear capacity, in.
V_c	=	ultimate shear strength of anchor (concrete failure), lbs.
V_d	=	shear design strength of concrete, lbs.
V_{su}	=	ultimate shear strength of anchor (steel failure), lbs.
V_a	=	shear design strength of anchor, lbs.
S	=	anchor spacing, in.
ϕ	=	strength reduction factor, dimensionless.

TABLE 1 -- RECOMMENDED SPACING AND EDGE DISTANCES -- SHEAR LOADS (V)

Anchor Embedment E	Type A Cast-in-Place Anchors		Type B Undercut Anchors		Type C & D Torque Controlled Expansion Anchors		Type E Deformation Controlled Expansion Anchors		Type F Chemical & Grouted Anchors		Type G Concrete Screws	
	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m
4.0D - < 6.0 D	3.50E	1.75E	3.50E	1.75E	3.50E	1.75E	3.50E	2.00E	2.00E	1.00E	2.00E	1.75E
6.0D - ≤ 8.0 D	2.00E	1.00E	3.00E	1.00E	2.00E	1.00E	3.00E	1.50E	1.50E	1.00E	1.50E	1.00E
>8.0 D	15D	10D	15D	10D	15D	10D	20D	10D	12D	10D	12D	10D

Type A - cast-in-place anchors: including headed anchor bolts, threaded inserts, welded studs, "L" and "J" bolts.

Type B - undercut anchors: including standard undercut, reverse undercut, and self-undercutting anchors.

Type C - heavy-duty torque-controlled sleeve anchors

Type D - torque-controlled expansion anchors: including wedge and sleeve anchors.

TABLE 2 -- RECOMMENDED SPACING AND EDGE DISTANCES -- TENSILE LOADS (P)

Anchor Embedment E	Type A Cast-in-Place Anchors		Type B Undercut Anchors		Type C & D Torque Controlled Expansion Anchors		Type E Deformation Controlled Expansion Anchors		Type F Chemical & Grouted Anchors		Type G Concrete Screws	
	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m	Anchor Spacing S	Edge Distance m
4.0 D - < 6.0 D	3.50E	1.00E	3.50E	1.00E	3.50E	1.50E	4.00E	2.00E	2.00E	1.00E	3.50E	1.50E
6.0 D - < 8.0 D	2.00E	1.00E	3.00E	1.00E	2.00E	1.00E	3.00E	1.50E	1.50E	1.00E	2.00E	1.00E
> 8.0 D	15D	6D	15D	6D	15D	6D	20D	10D	12D	6D	12D	6D

Type E - deformation-controlled expansion anchors: including stud anchors, drop-in anchors, and self-drilling anchors.

Type F - chemical and grouted anchors: including threaded rods or deformed bars set in pre-drilled holes with chemical compounds which include polyester resins, vinyl ester resins, and epoxies, and headed bolts set in pre-drilled holes with grout.

Type G - concrete screws.

TABLE 3 -- REDUCTION FACTORS

	Tension Capacity		Shear Capacity		
	Spacing (S) and Edge Distance (m)	Factor (F _t)	Spacing (S) and Edge Dist. (m)	Direction of Load	Factor (F _v)
Expansion Anchors (Type B, C, D, & E) ^{1,2}	$S_{min} = 0.50S$	0.7	$m_{min} = 0.50m^3$	toward edge not toward edge	0.5 0.6
	$m_{min} = 0.50m^3$	0.7	$S_{min} = 0.50S$	any direction	0.6
Chemical Anchors (Type F) ^{1,2}	$S_{min} = 0.50S$	0.7	$S_{min} = 0.50S$	any direction	0.6
	$m_{min} = 0.50m$	0.7	$m_{min} = 0.67m$	toward edge not toward edge	0.5 0.6
			$m_{min} = 0.5m$	toward edge not toward edge	0.25 0.4

¹ Linear interpolation is allowed for edge distances which fall between 0.5m and 1.0m, and anchor spacing which falls between 0.5S and 1.0S.

² Load reduction factors should be combined where applicable. In the case where three or more anchors are used, spacing reduction factors must be combined. Where two or more edge distances affect performance, edge reduction factors must be multiplied together. When a group of anchors is affected by both reduced spacing and reduced edge distances, the edge and spacing reduction factors must be multiplied together.

³ Reduced edge distances are not recommended for Type E anchors.

TABLE 4 -- RANGE OF REDUCTION IN TENSILE LOAD CAPACITY OF ANCHORS IN CRACKED CONCRETE (in percent) (Ref. 10)

Crack Width Δw (mm)	Cast-In-Place Anchors (%)	Undercut Anchors (%)	Heavy-duty Sleeve Anchors (%)	Torque-controlled Expansion Anchors (%)	Deformation Controlled Expansion (%)	Chemical and Grouted Anchors (%)	Concrete Screws (%)
0.4 (0.0157 in)	25-40	25-45	30-50	40-70	50-70	50-80	ID
0.8 (0.0315 in)	30-40	30-50	40-60	NR	NR	NR	ID

Notes: NR = Not Recommended, ID = Insufficient Data

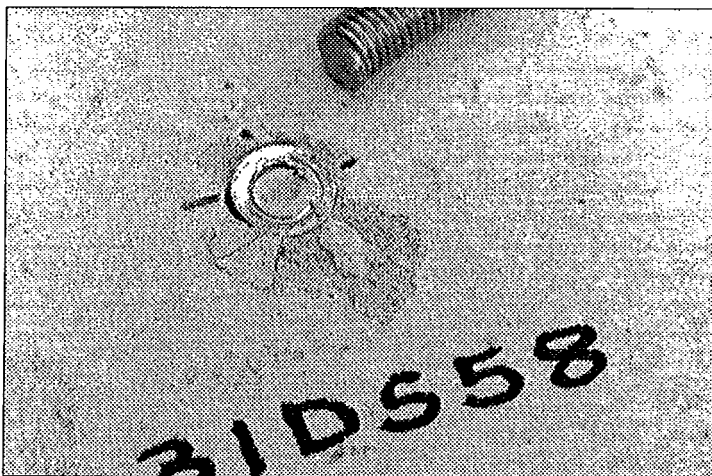


Fig. 1--Steel failure: the concrete crushes a small amount and the stress in the anchor results in an action that causes a smooth failure plane in the stud as the steel reaches its ultimate shear capacity

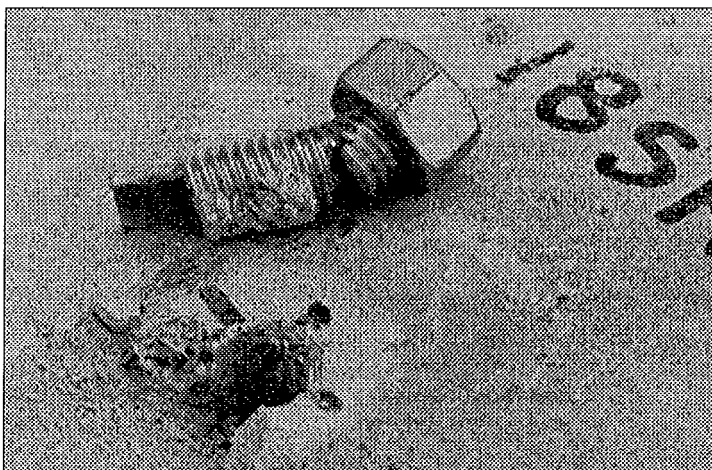


Fig. 2--Concrete crushing failure: the concrete surrounding the anchor crushes near the surface allowing the anchor to displace which creates a bending load ending in a steel rupture failure. This type of failure is common for anchors manufactured from brittle steels



Fig. 3--Concrete breakout failure: this type of failure generally occurs when anchors are installed close to an edge or corner (at 10 anchor diameters or less)

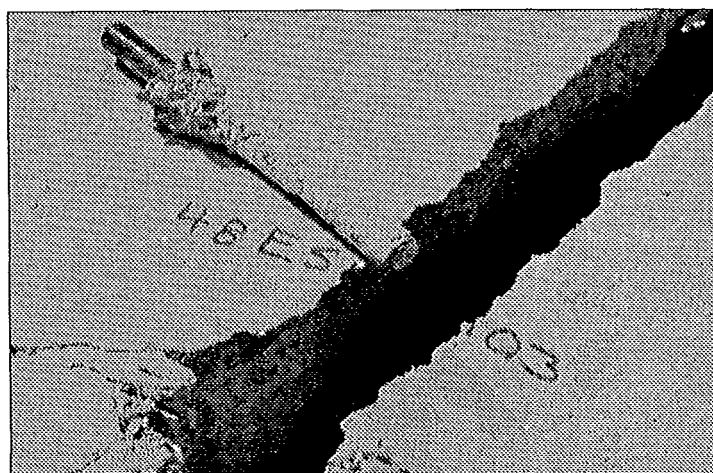


Fig. 4--Concrete splitting failure: the concrete slab or beam fails in bending, splitting the structural member. This type of failure is common for anchors installed near an edge of a thin, unreinforced slab or beam

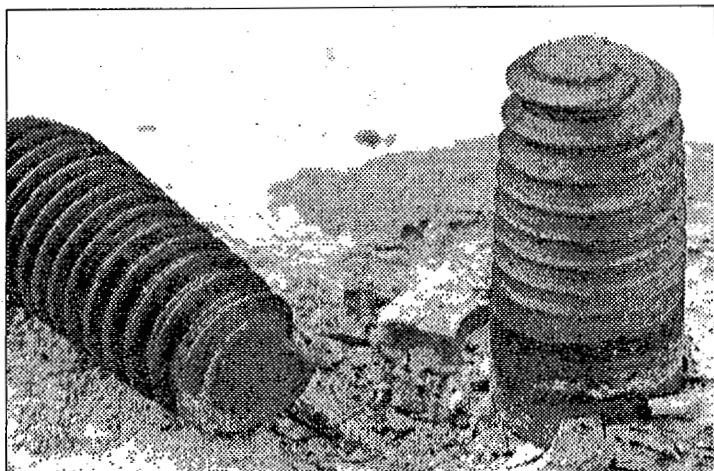


Fig. 5--Steel failure: the concrete stays confined and a ductile failure occurs as the steel reaches its ultimate tensile capacity. Anchors are generally installed at embedments of $9.0D$ or more

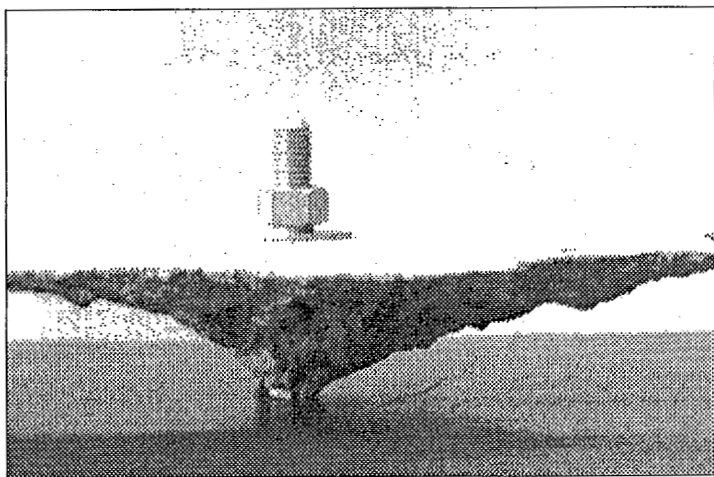


Fig. 6--Cone failure: the concrete fails in tension creating a shear cone. The cone starts at the bottom of the expansion mechanism and travels to the concrete surface at an angle which varies between 30 to 45 degrees. This type of failure is common when tension tests are performed on anchors installed at embedments between $4.5D$ and $6.0D$

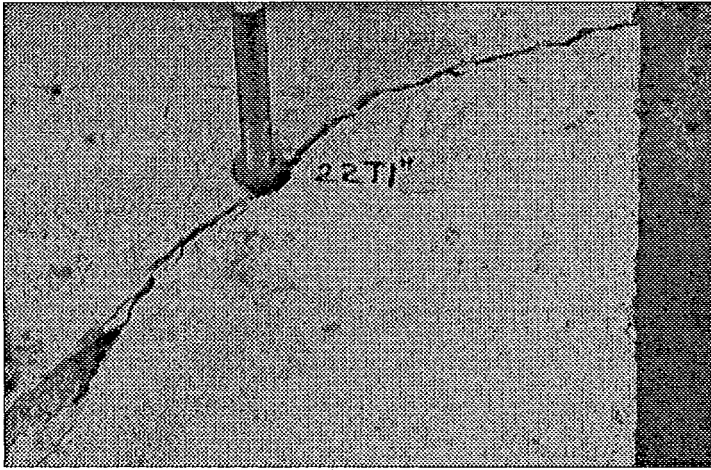


Fig. 7--Concrete failure: split structural member. The concrete slab or beam fails in bending. This type of failure is common for anchors installed in thin slabs and beams, or for anchors installed near a corner of a slab or beam



Fig. 8--Bond failure: the bond between the chemical resin or epoxy and the concrete fails, allowing the anchor to pull out. This type of failure is common for chemical anchors embedded between 6.0D and 9.0D, and is usually accompanied by a shallow concrete cone with a depth up to one-half of the stud embedment

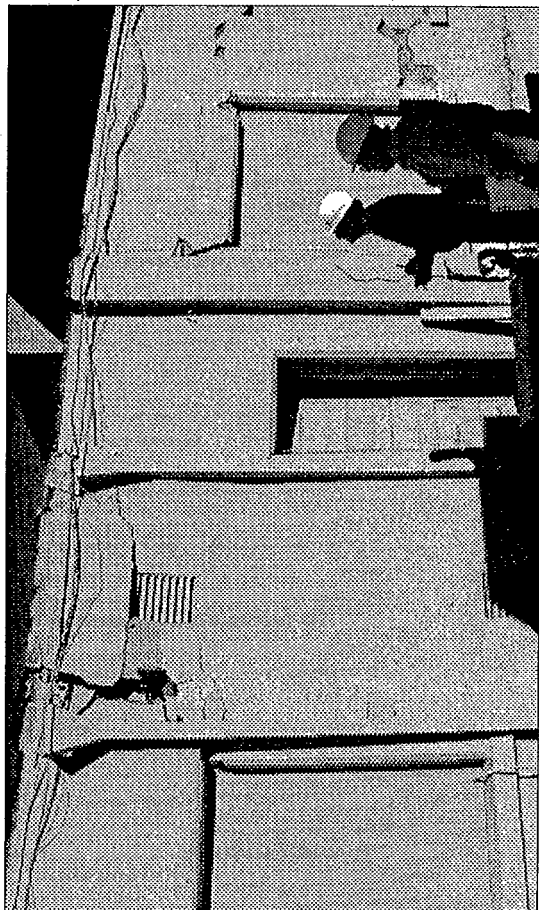


Fig. 9--Concrete anchors used in structures which are located in seismic zones 3 and 4 should be evaluated for performance in cracked concrete

SP 130-2

Evaluation of Expansion Anchor Ultimate Tensile Capacity Prediction Equations

by R. Walther, C. Sutton,
and D. Meinheit

Synopsis: Nine equations which predict ultimate tensile capacity for expansion anchor installations failing by formation of a concrete cone are reviewed. The equations predict the tensile capacity for anchors installed in unreinforced, uncracked concrete; group and edge effects are not considered. A data base consisting of the results from 927 tests was used to evaluate the accuracy of the prediction equations. Multiple regression statistics were utilized to ascertain how individual variables affected prediction accuracy.

For shallow embedments, all nine equations yield satisfactory, or conservative predictions. For deeper embedments, predicted capacity is less conservative. In general, empirical equations developed by curve-fitting experimental data are more accurate than semi-empirical models.

Keywords: Anchors (fasteners); concretes; expansion; failure mechanisms; performance; strength; tension

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INTRODUCTION

Nine equations, each predicting the ultimate tensile capacity for an expansion anchor that fails by formation of a concrete cone, are reviewed. This set of equations includes those most frequently referenced in current U. S. and European practice. The equations are applicable to individual anchors installed in unreinforced, uncracked concrete. Only installations which are free from the influences of adjacent free edges and/or neighboring anchors are considered.

The evaluations discussed in this paper determined:

1. how the equations perform with respect to each other,
2. how the equations perform with respect to a data base of 927 experimental test results, and
3. how individual equation variables affect prediction accuracy.

BACKGROUND - CONCRETE CONE FAILURE

Expansion anchors loaded in tension typically exhibit one of four failure modes: a) formation of a concrete cone, b) slip from the embedment concrete, c) anchor rupture or d) splitting of the embedment concrete member; combinations of these modes also occur. The typical failure modes are shown in Figure 1. The equations discussed in this paper predict concrete cone failure. An example of a concrete cone failure is shown in Figure 2.

Cone Failure Description

When an expansion anchor is loaded in tension, the tensile load is transmitted from the attachment through the anchor body to the expansion mechanism of the anchor. The expansion mechanism is typically located near the embedded end of the anchor. Most expansion anchors develop a lateral force normal to the hole wall.

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This normal force is necessary for the development of a frictional resistance to the applied tensile load. Other forces between the drill hole and the anchor are usually ignored.

As the applied tensile force on the anchor increases, a surface of principal tension stress develops within the concrete, radiating from the expansion mechanism towards the free surface of the embedment concrete. The angle, measured from the longitudinal anchor axis, defining the orientation of the principal tension stress surface has been reported to vary between 45 and 60 degrees. This angle tends to decrease with increasing embedment depth.^{1,2}

Eventually, the tensile stress along this surface exceeds the concrete tensile strength, and a cone of concrete is extracted. Failure cone depth ranges from 0.8 to 1.0 times the embedment depth.³ A schematic representation of a failure cone is shown in Figure 3, with those variables considered to be most influential on concrete cone capacity. It should be noted that the tensile strength of concrete is presumed to control the concrete cone failure strength; however, the tensile strength, as a variable with respect to this failure mode, is represented as a function of the concrete compressive strength, f'_c .

The embedment depth, shown in Figure 3, is measured from the concrete surface to the deepest contact point between the expansion anchor and the drilled hole.³ The failure cone angle is measured from the longitudinal anchor axis to the failure surface.

PREDICTION EQUATIONS

Nine equations^{1,2,3,5} which predict the concrete cone strength of individual anchor installations are shown in Tables 1 and 2. The prediction equation, shown in Table 1, recommended by the American Concrete Institute (ACI) Committee 349, Concrete Nuclear Structures, and the Prestressed Concrete Institute (PCI) are identical in their format but differ in their derivations. The equations developed by ACI-PCI and Braestrup, et al. have been semi-empirically derived. The remaining equations given in Table 1 were developed as best-fit models of experimental test data. It should be noted that Bode and Roik's equation was derived from headed stud data, with the head diameter taken as zero.

The equations shown in Table 1 are similar in that each makes use of two variables: embedment depth (l_e) and concrete compressive strength (f'_c), as an index of concrete tensile strength. For equations shown in Table 1, the embedment depth is raised to a power of 1.5 or 2.0 and the power to which the concrete compressive strength is raised is either 1/2, 2/3 or 1.

The remaining equations, shown in Table 2, differ slightly from those presented in Table 1, i.e. they involve different variables. Schwarz makes use of an effective embedment depth which is defined as the embedded depth less one bolt diameter. The effective depth is used to account for anchor displacement prior to failure. Cannon in his equation has added a third variable to account for the increase in failure cone angle as embedment depth decreases.

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EVALUATION RESULTS

Several techniques were used to evaluate how the equations perform relative to each other, to actual test data, and how the individual variables affect prediction accuracy. The evaluation results are discussed according to the technique used to make the comparison.

Contour Curves

Contour curves have been developed and are shown in Figure 4. In this figure, the dependent variable (strength) is plotted against each independent variable for constant values of the other independent variable. In Figure 4a, predicted strength is plotted with respect to embedment depth for a 4000 psi (28 MPa) concrete compressive strength. Capacities predicted by the equations differ as embedment depth increases; e.g., at 4 in. (102 mm) embedment, predicted strength varies by 8000 lbs (35.6 kN) while at 8 in. (203 mm) embedment, predicted strength varies by 30,000 lbs (133.4 kN). Figure 4b shows a contour curve in which predicted strength is plotted with respect to concrete compressive strength for a constant 4.5 in. (114 mm) embedment depth. In this figure, the predicted strengths vary by 5000 lbs (22 kN) at a concrete compressive strength of 3000 psi (21 MPa) and 14,000 lbs (62 kN) at 7000 psi (48 MPa). Therefore, for the range of typical compressive strengths 3000 to 7000 psi (21 to 48 MPa), the equations predict capacities which can vary from 50 to 70 percent, with increased variability at higher compressive strengths.

Because of the significant differences in the capacities predicted by these equations, equation performance with respect to expansion anchor test results should be understood so that appropriate safety factors can be chosen.

Data Base

A data base of 927 expansion anchor test results was collected from various sources⁶ so that the equations in Tables 1 and 2 could be evaluated. The collected data was identified by anchor manufacturer, anchor type, anchor shank diameter and length. Installation data, when available, included embedment depth, installation torque, number of turns of the anchor nut past finger-tight and the installed anchor angle measured with respect to the longitudinal anchor axis.

The reported compressive strength of the embedment concrete is included as part of the data base information. In general, compressive strength was determined from standard cylinder tests, performed on or proximate to the day of the anchor test. However, in some instances the reported compressive strength was an average or minimum value given for the period of days over which the anchor tests were conducted. Concrete age is also given when available.

The principal characteristics of the data base are summarized in Table 3. Test results on two anchor types, torque and displacement controlled, were studied. Examples of torque and displacement controlled anchors are shown in Figures 5 and 6. These anchors differ in the method by which lateral expansion of the anchor against the hole wall is induced. For torque controlled anchors, an anchor is set when a predefined torque has been applied to the anchor. Displacement controlled anchors are set when the anchor shell or expansion cone has been forced to

undergo a prescribed displacement. The term set indicates that a given amount of lateral expansion has been developed.

Histograms

Each prediction equation was used to calculate the ratio of experimental to predicted capacity, P_{exp}/P_{calc} , for each of the 927 test results. Plots of the frequency distributions of this ratio can be used to evaluate the performance of these equations. Ideally, an equation that has a prediction ratio with a frequency distribution normally distributed about unity and a small standard deviation would be considered a good predictor of the data. A ratio of unity indicates the actual capacity is equal to the predicted capacity. Ratios greater than unity represent conservative predictions, while ratios less than unity represent unconservative predictions.

The frequency distributions of P_{exp}/P_{calc} developed for each equation are shown in Figure 7. The mean and standard deviation of the data base information for each equation are summarized in Figure 8. The ACI-PCI equation is the most conservative predictor with a mean ratio of 1.62. A large standard deviation of 0.65 is also associated with this equation. The best predictor of the data is the Bode and Roik equation with a mean ratio of 1.03 and a standard deviation of 0.31.

From Figure 7, it can be seen that the test results plot as positively skewed distributions. By separating the torque and displacement controlled anchor test results, the positive skew is shown to be linked to the relative performance characteristics of these two different anchor types. Displacement controlled anchors tend to yield experimental to calculated ratios which are greater than those of torque controlled anchors. This is illustrated in Figure 9 for each of the prediction equations.

A summary of the key information presented in Figures 7, 8 and 9 is shown in Table 4. The ACI-PCI, P-W and BRA equations, all of which include an l_e^2 term, produce frequency distributions with large positive skews. The positive skew results partially from the difference between means of torque and displacement controlled anchors. The smallest difference between means for the two different anchor types is 0.22 for the CAN equation, and the largest difference is 0.91 for the ACI-PCI equation. If torque and displacement controlled anchor test results are considered separately, the EFM and CAN equations are the best predictors for displacement controlled anchors and the P-W and BRA equations are the best predictors for torque controlled anchors.

Coefficient of variations have been calculated for each prediction equation and are given in Table 4, column 8. Equations that predict conservative capacities generally yield a higher coefficient of variation than those equations which give less conservative predictions.

Plots of P_{exp}/P_{calc} versus l_e/d

Within the expansion anchor data base, displacement and torque controlled anchors have ratios of l_e/d which range from 1.5 to 4.5 and 3.0 to 8.0, respectively. When P_{exp}/P_{calc} was plotted against l_e/d , it is observed that as l_e/d increases the ratio of P_{exp}/P_{calc} decreases, often to values less than unity, unconservative predictions⁶. The decrease in the ratio of P_{exp}/P_{calc} is thought to be partially attributed to a significant amount of slip prior to concrete rupture when the anchor embedment is such

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to cause a larger l_e/d ratio. It has also been reported that the failure mode for torque controlled expansion anchors changes from cone failure to slip failure when the embedment depth exceeds 4 to 6 bolt diameters.^{1,4} This, however, does not preclude cone failures or anchor rupture from occurring at embedments in excess of these depths. Since the prediction equations become increasingly unconservative as the l_e/d ratio increases, their use is inappropriate for deeply embedded expansion anchors which experience slip type failure prior to developing the concrete cone capacity.

Analysis of Residuals

In order to determine how the individual variables within the prediction equations affect prediction performance, an analysis of the residuals is presented. A residual is the difference between the observed anchor capacity and the corresponding predicted (calculated) capacity.

To apply multiple regression statistics to the various prediction equations, it was necessary to transform the nine equations into simple linear relationships with two independent variables. This was accomplished by taking the logarithm of both sides of the prediction equation. An example of this transformation is given below:

$$\text{Original Prediction Equation: } P_o = A (l_e)^B (f'_c)^C$$

$$\text{Linearized Model: } \log(P_o) = \log(A) + B \log(l_e) + C \log(f'_c)$$

In these equations, A, B, and C are constants, $\log(l_e)$ and $\log(f'_c)$ are independent variables, and $\log(P_o)$ is the dependent variable.

The residual analysis included plotting the residuals ($P_{\text{experimental}} - P_{\text{calculated}}$), arranged in ascending order, against a probability. The probability is calculated as follows:

$$\text{Probability} = \frac{i - 0.5}{n} \times 100$$

where, n = total number of residuals
i = position of ordered residual within n residuals.

Such a curve of the residuals and probabilities is called a probability plot. When a probability plot is linear, the data are normally distributed about the mean. The mean of the probability plot for a properly fitted regression model equals zero. Probability plots which are not linear indicate the extreme ends of the normal distribution have either too many or too few data points, or the data are positively or negatively skewed.

The analyses conducted also included plots of the residuals versus each of the independent variables. These plots reveal model defects with respect to the plotted variable. Again, for a properly fitted regression model, the residuals are evenly distributed about zero for all values of the independent variable.

Results of the regression analysis are presented below.

Probability Plots -- The probability plots generated for each prediction equation show a linear relationship with only slight deviations from linearity at the ends of the curve. Thus indicating the data base is, in general, normally distributed with

respect to each prediction equation. A representative probability plot, generated for the BOD equation, is shown in Figure 10.

Based on the evaluation of the frequency distributions of P_{exp}/P_{calc} , if a prediction equation is determined to be a good analytical model then the probability plot for that prediction equation yields a probability of 50 percent for residuals having a value of zero; thus indicating the data is equally distributed above and below the regression surface. Figure 10a exhibits this characteristic.

Residuals versus Independent Variables -- Residuals were calculated and plotted against the independent variables of the linearized regression model, $\log(f'_c)$ and $\log(l_e)$. Selected residual plots are shown in Figure 11.

All prediction equations produce residual values which appear to be independent for all values of $\log(f'_c)$, as seen in Figure 11; however, the residuals were observed to decrease as $\log(l_e)$ increased, implying some dependence. Residuals plotted against $\log(f'_c)$ generally maintained a constant mean for all values of the independent variable. Plots of residuals versus $\log(l_e)$ for equations considered to be good predictors also maintained a nearly constant mean over the range of the independent variable. However, for the poorer prediction equations, the mean of the residuals was observed to decrease as the independent variable, $\log(l_e)$, increased. Those equations determined by this analysis to be poor predictors have been semi-empirically developed. Equations developed as best fit curves to experimental data were observed to be better predictors of the mean of the 927 test results.

The regression analysis results indicate the influence of f'_c in the prediction equations is in the correct proportion. Changes in the value of the exponent of f'_c will not markedly alter the residual plots. Residual plots of l_e indicate the influence of this variable either is not in the correct proportion for the prediction of concrete cone strength or that an additional variable should be added to improve prediction accuracy.

Semi-empirically developed equations show the influence of l_e is not in correct proportion to the prediction of concrete cone strength. Based on the available expansion anchor behavior literature¹, it is known that as embedment depth increases the failure cone angle decreases. As embedment depth increases, slip of the anchor prior to failure also increases. Therefore, the inclusion of a variable which accounts for the change in failure cone angle or amount of slip prior to failure would improve the prediction equation accuracy.

The residual plots of $\log(l_e)$ for the experimentally developed equations do not show a similar need for an additional variable because the influence of failure cone angle and slip are implicitly included in the test result.

Additional Findings from Regression Analysis -- Using least squares regression analysis techniques and the 927 expansion anchor test results, the following best-fit model, using the variables of embedment depth and concrete compressive strength, was derived.

$$P_c = 62.4 l_e^{1.579} f'_c^{0.397}$$

Since the above equation is a best-fit equation for the data

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base, the residuals with respect to each independent variable should be centered about zero and have a constant distribution over the full range of each variable. Figure 12 shows the residual plot of $\log(l_e)$. As with the other nine prediction equations, the residuals plotted against $\log(l_e)$ are centered about zero but the distribution is not constant over the variable range. By separately plotting the residuals for the 380 displacement controlled anchor test results (Figure 13a) and the 547 torque controlled anchor test results (Figure 13b), the residuals are seen to be more constant with embedment depth. These plots may help explain the influence of embedment depth on the prediction equation accuracy.

Torque controlled anchors yield residuals centered about zero with a small variance. The residuals for displacement controlled anchors show a somewhat larger variance but are also centered about zero. When the residuals are plotted as in Figure 12, the shape of the residual plot is noted to be similar to residual plots for the ELG, EFM, and B&R equations. These equations have been determined to be the best predictors of ultimate anchor capacity.

A somewhat simpler form of Eqn 1 can be obtained if the exponents of embedment depth and compressive strength are rounded to the more convenient values 1.5 and 0.5, respectively. Assuming a fixed exponent on l_e and f'_c and determining the value for the constant term, the following equation results.

$$P_c = 28.7 l_e^{1.5} f'_c^{0.5} \quad (\text{Eqn 1})$$

This equation is identical to that developed by Bode and Roik and has a correlation coefficient of 0.98.

The above analysis has shown that torque and displacement controlled anchors behave differently with respect to embedment depth. Separating the test results for torque and displacement controlled anchors shows that the best-fit regression models for each anchor type are similar but not identical. The following relationships have been empirically obtained for torque controlled anchors,

$$P_c = 34.6 l_e^{1.721} f'_c^{0.432}$$

and for displacement controlled anchors,

$$P_c = 30.9 l_e^{1.585} f'_c^{0.514}$$

If the exponents of embedment depth and compressive strength are arbitrarily taken as 1.5 and 0.5, respectively, note that these exponents are very close to those for the empirically derived displacement controlled equation, and regression statistics are used to solve for the coefficient term in the equation, the following relationship is determined for torque controlled anchors,

$$P_c = 24.4 l_e^{1.5} f'_c^{0.5} \quad (\text{Eqn 2})$$

The similarly obtained relationship for displacement controlled anchors is

$$P_c = 36.5 l_e^{1.5} f'_c^{0.5} \quad (\text{Eqn 3})$$

All three equations (Eqn 1, 2 and 3) using the 1.5 and 0.5

exponents are plotted in Figure 14 and have a high correlation coefficient to the respective test results for the two anchor types. As expected, Eqn 1 represents the compromise of the entire data base.

CONCLUSIONS

Nine equations which predict ultimate tensile capacity for expansion anchors failing by formation of a concrete cone have been reviewed. Ultimate tensile capacity is influenced by a number of test and installation variables, but the variables which appear most significant are: a) embedment depth; b) compressive strength of the embedment concrete; c) failure cone angle, and d) slip prior to concrete rupture. The treatment of the significant variables by the nine equations results in varied capacity predictions for all ranges of the independent variables.

The Bode and Roik equation has been determined to be the best predictor of the mean of 927 expansion anchor test results used in this study. Frequency distributions of the ratio of the experimental to predicted capacity, P_{exp}/P_{calc} , exhibit a positive skewness when P_{exp}/P_{calc} is large. The typical positive skew of the distribution is due to the fact that displacement controlled anchors consistently yield larger P_{exp}/P_{calc} ratios than torque controlled anchors. When the 380 displacement and 547 torque controlled anchor test results were considered separately, the Eligehausen, et al. and Cannon equations satisfactorily predict capacities of displacement controlled anchors and the Fussill-Wachtsmuth and Braestrup, et al. equations adequately predict capacities of torque controlled anchors.

Comparison of the P_{exp}/P_{calc} ratio to the embedment depth to diameter ratio, l_e/d , indicated the prediction equations tend to predict unconservative capacities for expansion anchors when the l_e/d ratio is in excess of 5. This suggests that use of the prediction equations is probably inappropriate for deeply embedded expansion anchors with l_e/d ratios in excess of 5.

The independent variables of the prediction equations were found to affect prediction accuracy. A study of the residuals, the difference between predicted and measured capacities, indicated concrete compressive strength is important to the prediction of ultimate anchor capacity. Further, the value of the exponent used with this variable in the nine prediction equations did not significantly affect prediction accuracy. Conversely, the residual analysis conducted with respect to embedment depth indicated that treatment of this significant variable in the equations greatly affects prediction accuracy. Because changes in embedment depth can influence additional variables, namely failure cone angle and amount of slip prior to failure, small alterations in its exponent result in large variations in capacity predictions.

The behavior of displacement controlled expansion anchors and torque controlled anchors can also be treated separately. Displacement controlled test results are more representative of a behavior that is controlled by the tensile strength of concrete.

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TABLE 1 -- CAPACITY PREDICTION EQUATIONS

Eqn (1)	Author (2)	Prediction Equation (3)
ACI-PCI	ACI, Comm. 349 Shaikh & Yi (PCI)	$4 \pi l_e^2 \sqrt{f'_c}$
BRA	Braestrup, et al.	$0.31 l_e^2 f'_c$
ELG	Eligehausen	$8.7 l_e^{1.54} f_c'^{2/3}$
EFM	Eligehausen, et al.	$35.8 l_e^{1.5} \sqrt{f'_c}$
P-W	Pussill-Wachtsmuth	$3.84 l_e^2 f_c'^{2/3}$
B&R	Bode & Roik	$28.7 l_e^{1.5} \sqrt{f'_c}$

TABLE 2 -- CAPACITY PREDICTION EQUATIONS

Eqn (1)	Author (2)	Prediction Equation (3)
SCH*	Schwarz	$22.2 (l'_e)^2 \sqrt{f'_c}$
CAN†	Cannon	$4 \pi (l_e \tan \theta)^2 \sqrt{f'_c}$

*, for $l'_e = l_e - (1 \text{ bolt diameter})$

†, for $l_e < 3"$, $\theta = 62 - 1.11 l_e^2$, degrees

, for $3" \leq l_e < 6"$, $\theta = 45 + 0.79 (6 - l_e)^2$, degrees

, for $l_e \geq 6"$, $\theta = 45$, degrees

TABLE 3 -- SUMMARY OF DATA BASE

Total Number of Test Results*	927
Torque Controlled Anchors	547
Displacement Controlled Anchors	380
Range of Embedment Depths	1 in. to 8 in.
Range of $\frac{l_e}{D}$ ratios	1.5 to 8.0
Range of Compressive Strength	1500 psi to 7200 psi

TABLE 4 - SUMMARY OF FREQUENCY DISTRIBUTIONS

Equation (1)	Anchor Type (2)	For $\frac{P_{exp}}{P_{calc}}$					COV(%) (8)
		Distribution (3)	Range (4)	Mean (5)	St Dev (6)	Median (7)	
ACI-PCI	all torque displacement	Large Positive Skew	0.2-4.2	1.61	0.65	1.10	40
		Positive Skew	0.2-2.8	1.24	0.34	1.10	27
		Positive Skew	0.8-4.2	2.15	0.62	1.90	29
CAN	all torque displacement	Fairly Normal	0.2-1.6	0.77	0.25	0.77	32
		Fairly Normal	0.2-1.4	0.67	0.22	0.67	33
		Positive Skew	0.4-1.6	0.91	0.22	0.90	24
ELG	all torque displacement	Slight Positive Skew	0.2-1.6	0.84	0.27	0.87	32
		Fairly Normal	0.2-1.2	0.68	0.16	0.69	24
		Fairly Normal	0.4-1.8	1.07	0.23	1.07	22
EFM	all torque displacement	Slight Negative Skew	0.2-1.6	0.83	0.25	0.80	30
		Fairly Normal	0.2-1.2	0.68	0.15	0.69	22
		Fairly Normal	0.4-1.6	1.04	0.21	1.03	20
SCH	wedge only	Positive Skew	0.4-2.4	1.21	0.39	1.15	32
P-W	all torque displacement	Large Positive Skew	0.4-3.6	1.35	0.56	1.23	41
		Positive Skew	0.4-2.2	1.03	0.30	0.99	29
		Positive Skew	1.0-3.6	1.82	0.54	1.73	30
BRA	all torque displacement	Large Positive Skew	0.4-4.2	1.38	0.59	1.25	43
		Positive Skew	0.4-2.4	1.01	0.34	0.99	34
		Positive Skew	0.8-4.2	1.89	0.62	1.76	33
B&R	all torque displacement	Slight Positive Skew	0.4-1.8	1.03	0.31	1.00	30
		Fairly Normal	0.4-1.4	0.85	0.19	0.87	22
		Fairly Normal	0.6-1.8	1.29	0.26	1.28	20

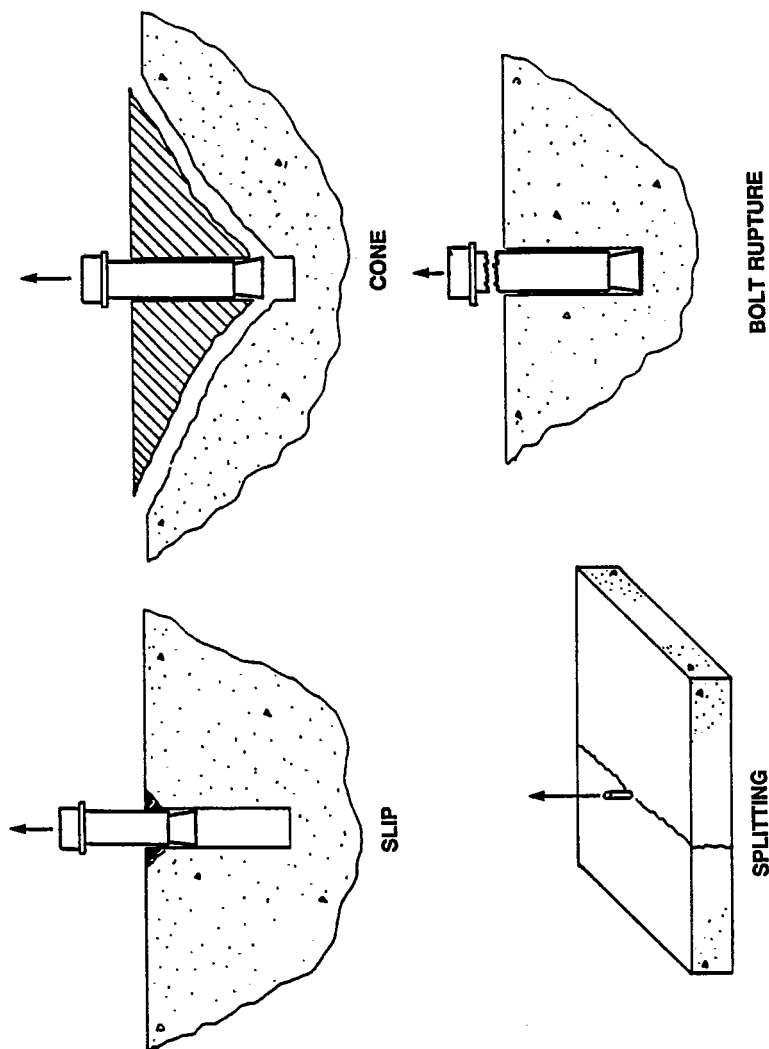


Fig. 1--Typical failure modes of expansion anchors loaded in tension

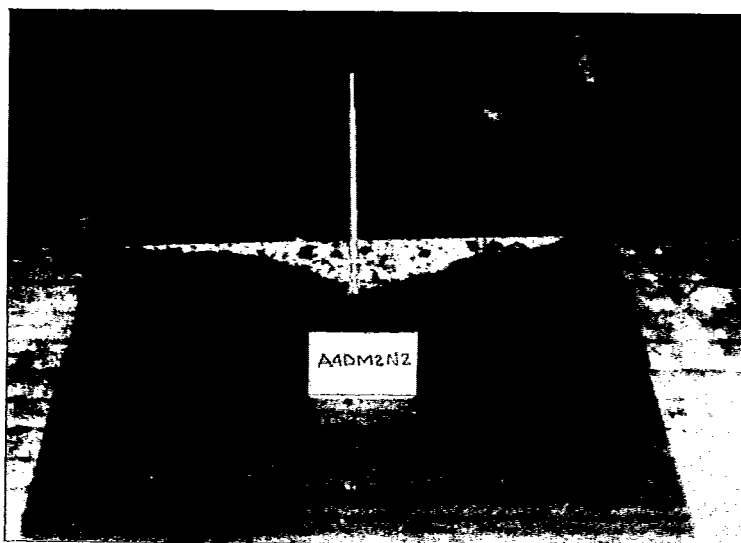


Fig. 2--Typical concrete cone failure

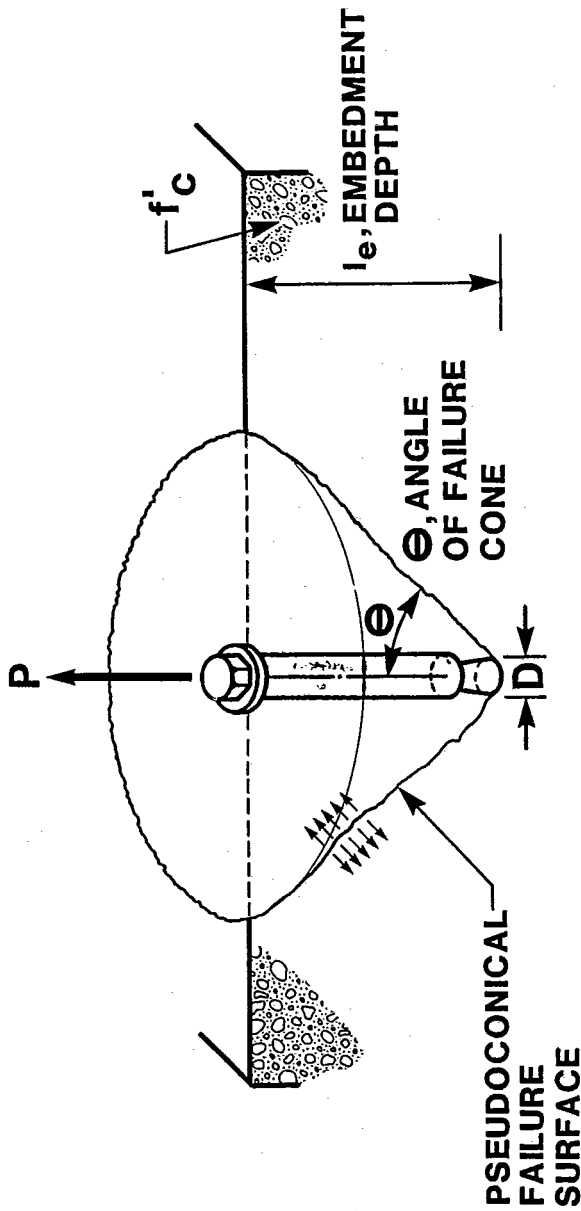
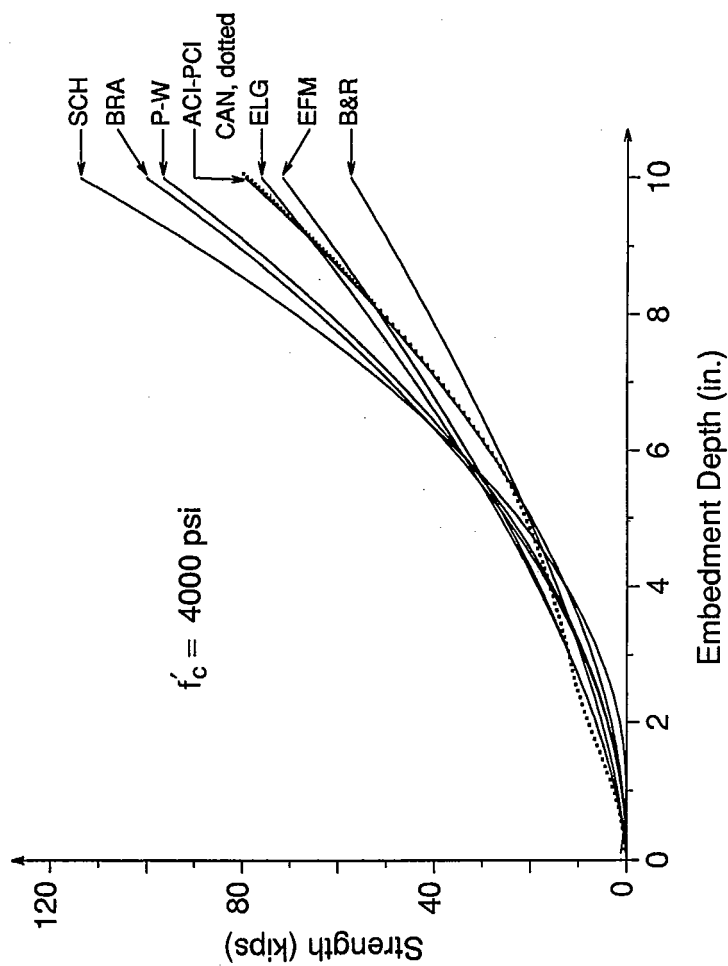


Fig. 3--Schematic cone failure



a) Predicted strength as a function of embedment depth

Fig. 4--Contour curve

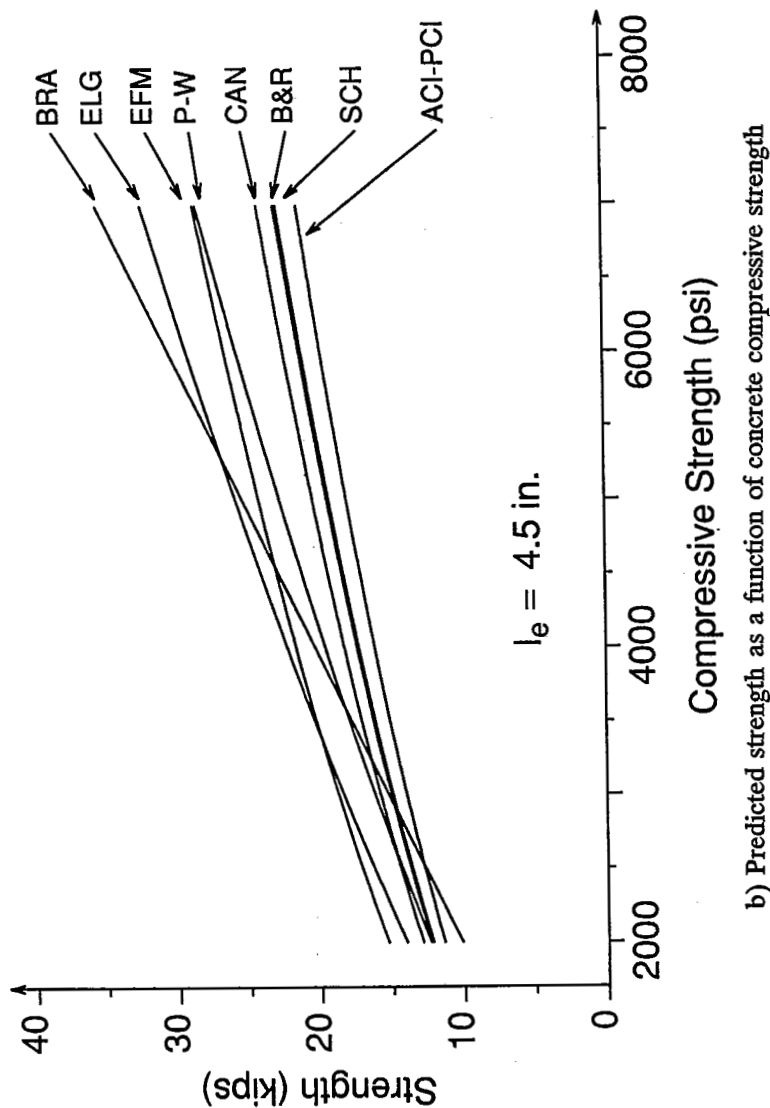


Fig. 4 cont.--Contour curve

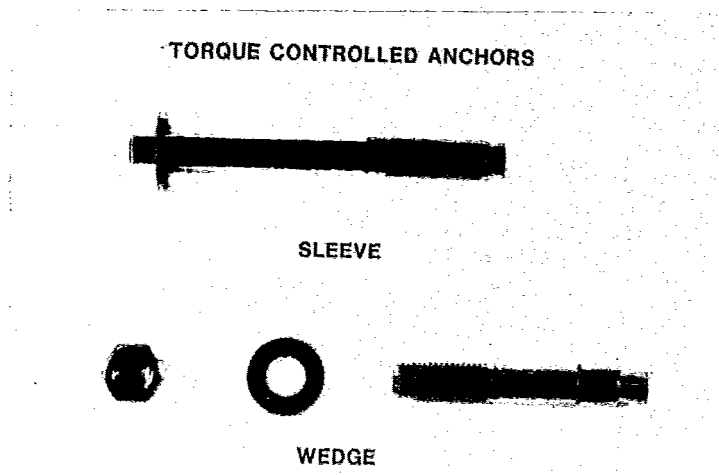


Fig. 5--Torque controlled anchors

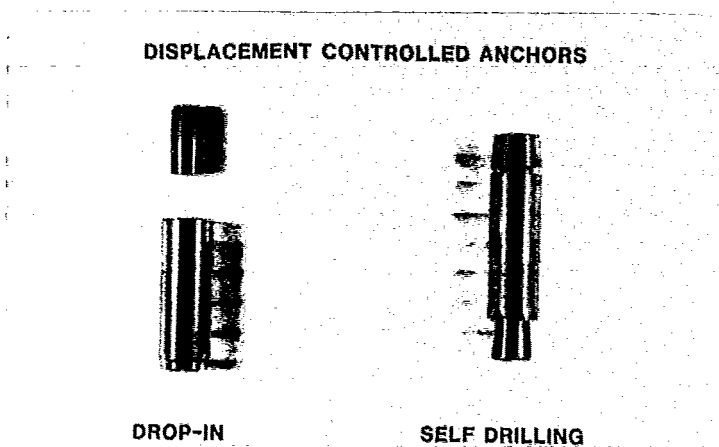


Fig. 6--Displacement controlled anchors

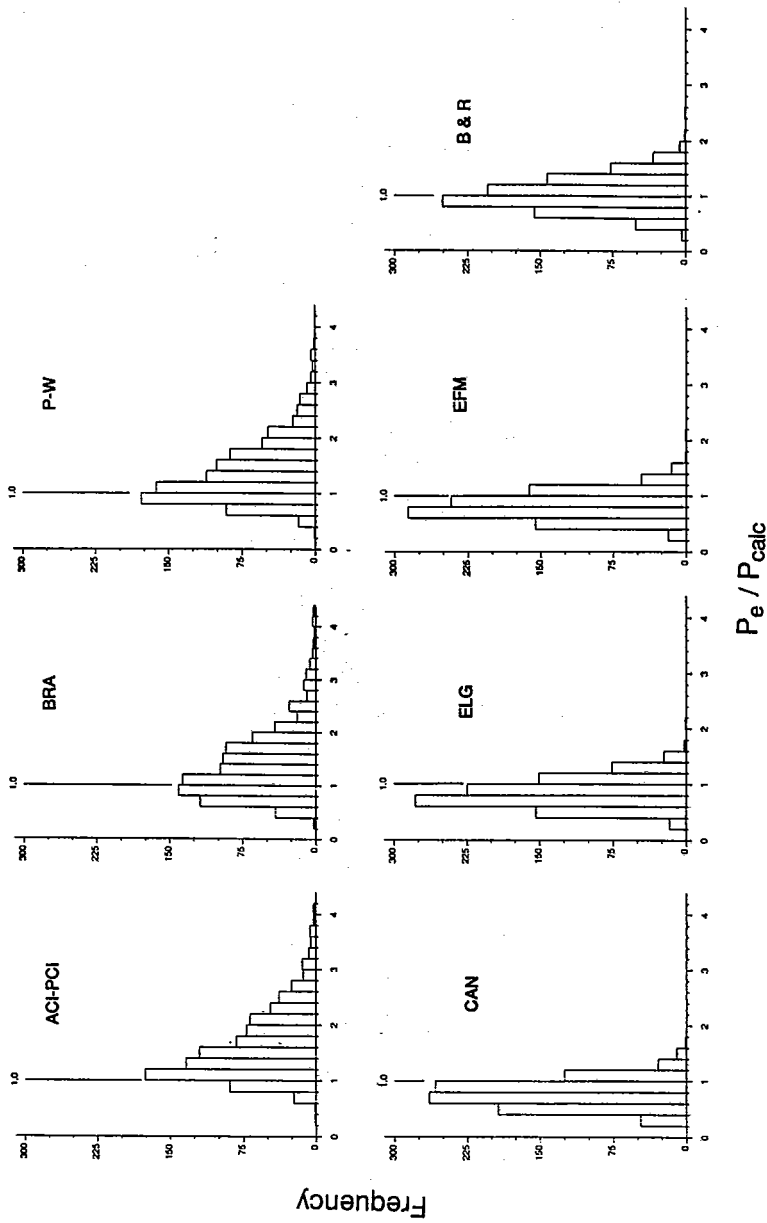
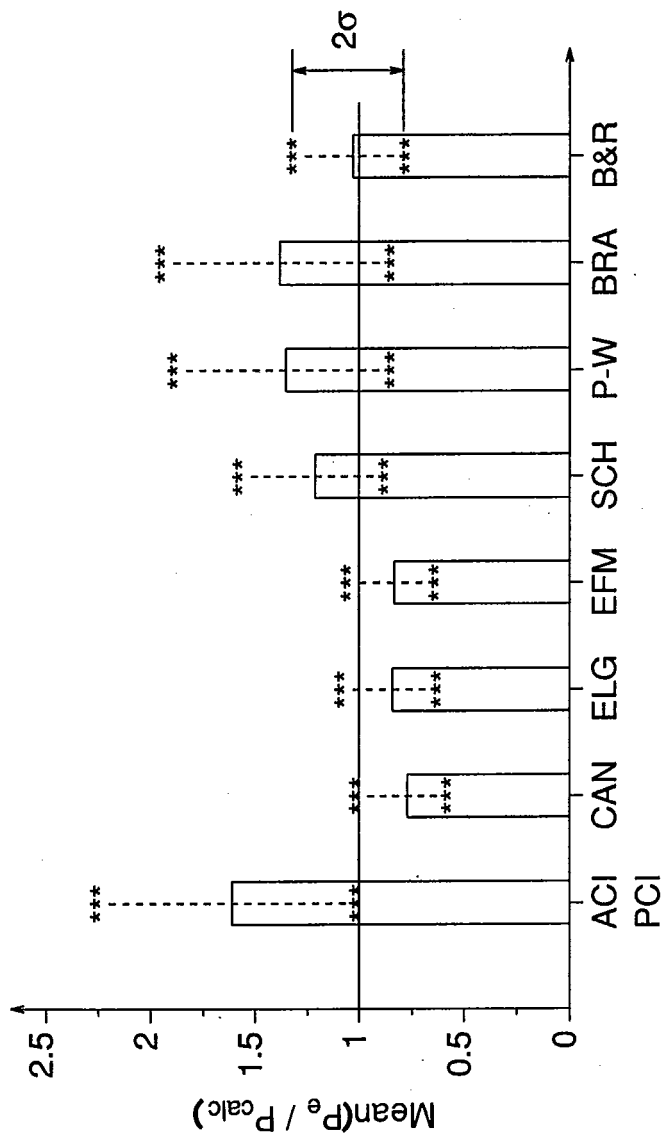


Fig. 7--Frequency distribution plotted for all anchor types



Prediction Equation

Fig. 8--Summary of frequency distributions

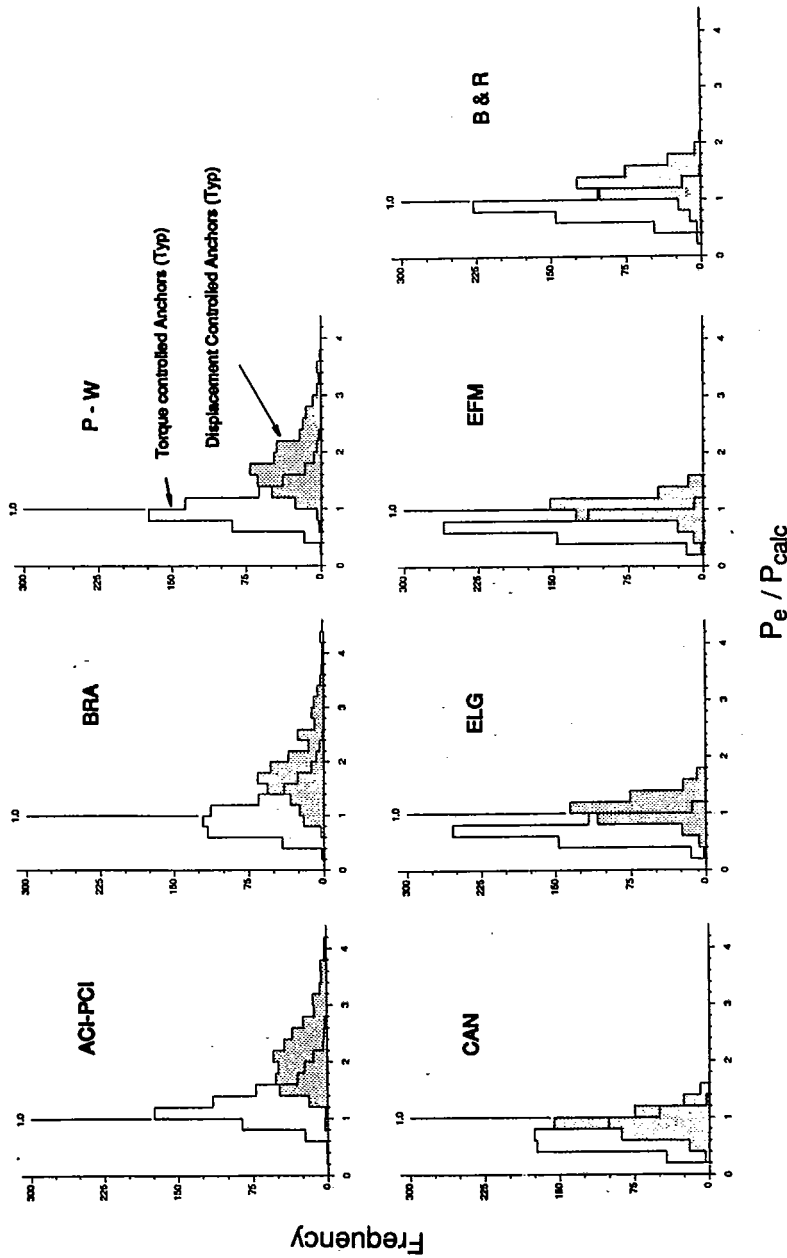
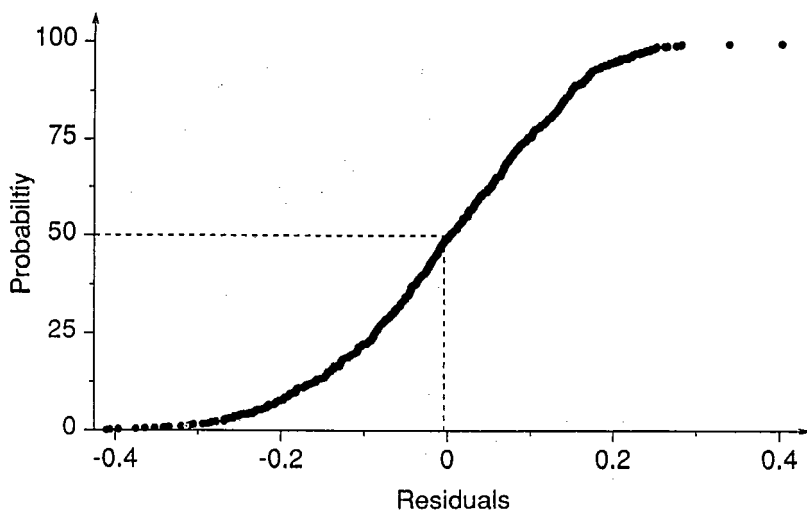
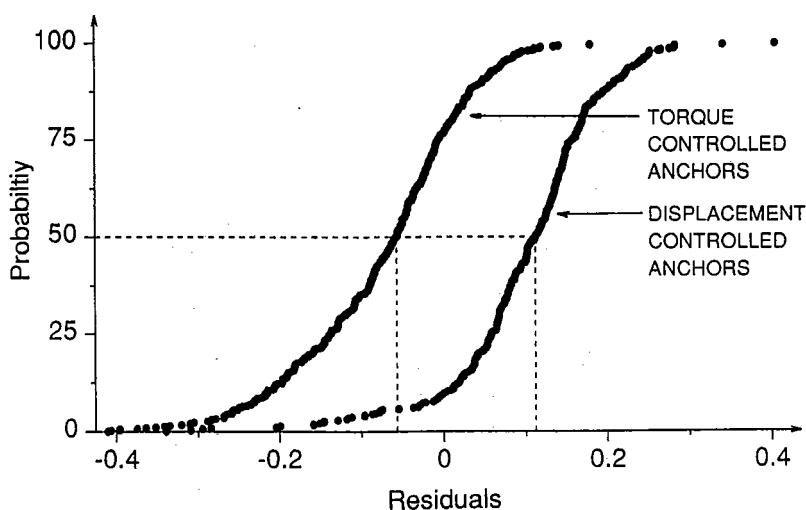


Fig. 9--Frequency distribution plotted individually for torque and displacement controlled anchors



a.



b.

Fig. 10--Probability plot: BOD

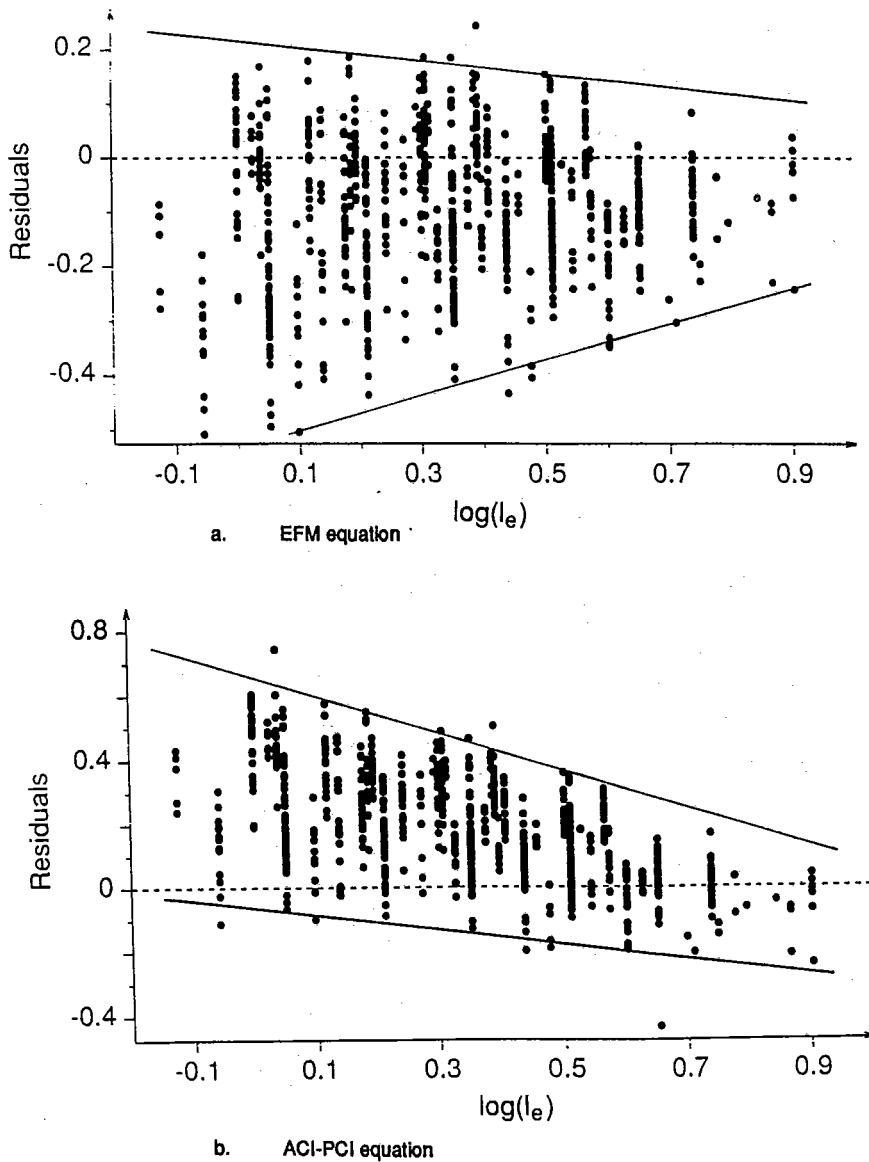
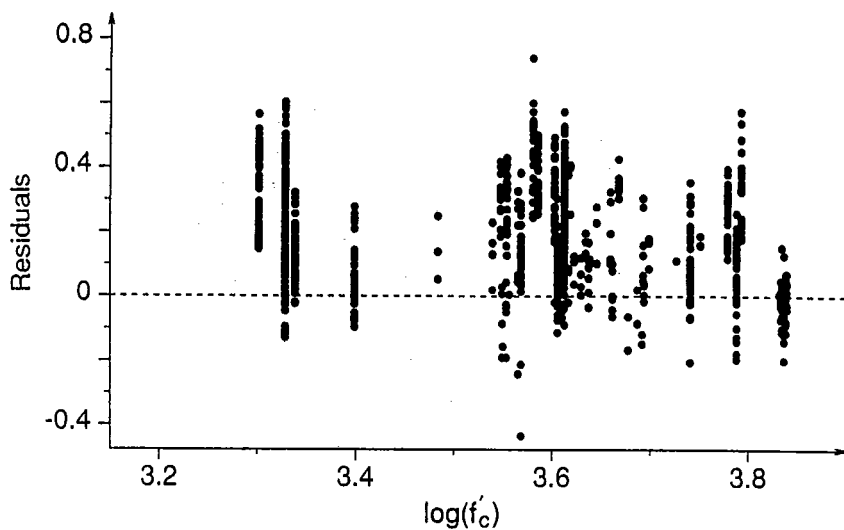
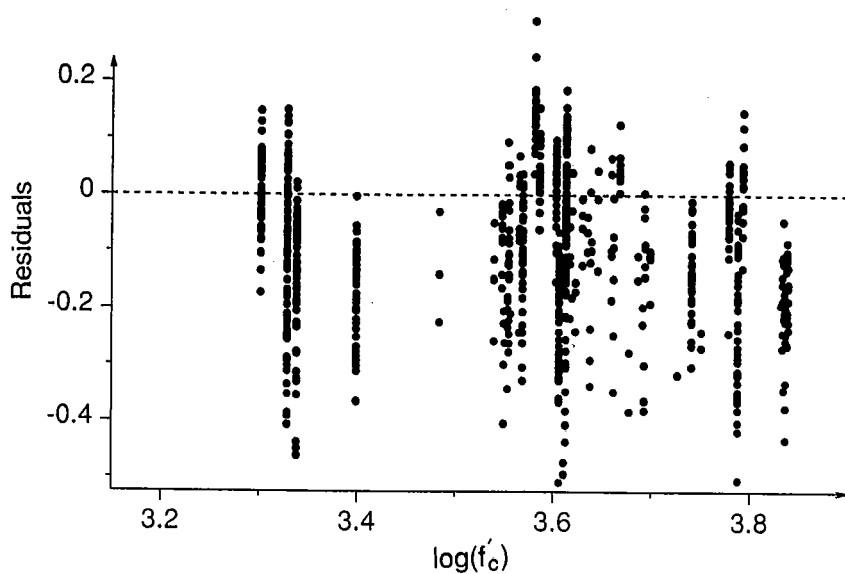


Fig. 11--Residual plots



c. EFM equation



d. ACI-PCI equation

Fig. 11 cont.--Residual plots

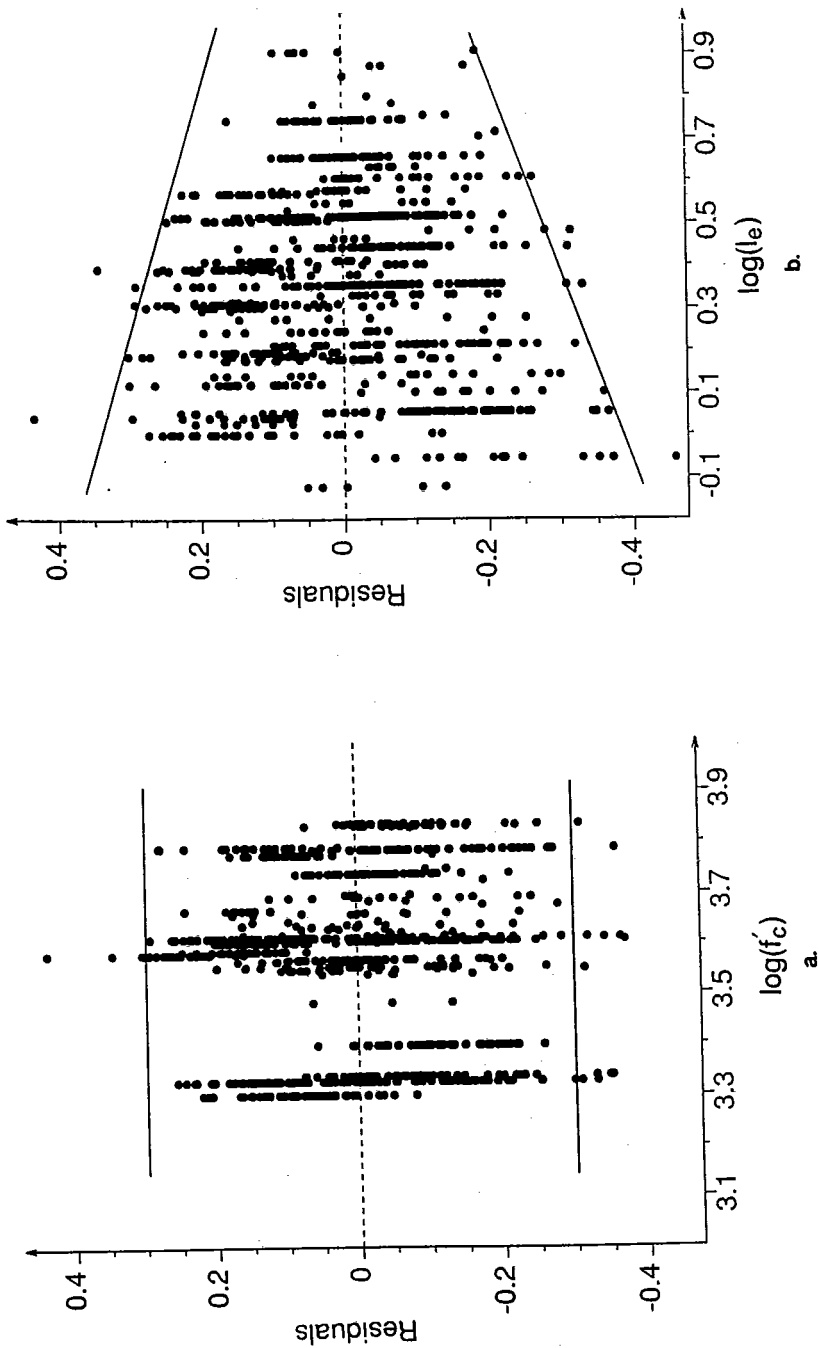


Fig. 12--Residual plots -- Equation 1